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Advectively dominated flows in the cores of giant elliptical galaxies: application to M60 (NGC 4649)

T. Di Matteo[1] and A. C. Fabian[1]
[1]Institute of Astronomy, Madingley Road, Cambridge, CB3 OHA

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ABSTRACT
It has been suggested that the final stages of accretion in present–day giant elliptical galaxies occur in an advection-dominated mode. The poor radiative efficiency of this accretion solution accounts for the fact that massive black holes, which are believed to reside in the centres of these galaxies, do not have the luminosities expected if accretion from the hot interstellar medium occurs at the Bondi rate. We discuss the advection-dominated solution for the nucleus of M60 (NGC 4649) and show that accretion at the Bondi rate is consistent with the core flux from radio to X-ray. This solution allows for a black hole mass of $\sim 10^9\,\mathrm{M}_\odot$ as required by independent arguments. The successful application of this model to both M60, and previously to the well known nucleus of M87, suggests that accretion of hot gas in an elliptical galaxy creates the ideal circumstances for advection-dominated accretion flows to operate.

Key words: galaxies: individual: M60, galaxies: active, accretion, accretion discs

1 INTRODUCTION

Most nearby, large elliptical galaxies should host a massive black hole left over from an earlier quasar phase (Fabian & Canizares 1988; Fabian & Rees 1995). Giant elliptical galaxies also contain an extensive hot halo which provides a minimum fuelling level for accretion. This leads to a problem. Fabian & Canizares (1988) have determined a limit to the accretion rate for a sample of bright elliptical galaxies produced using the classical Bondi (1952) formula. They concluded that if the radiative efficiency of accretion is ~ 10 per cent, then all such nuclei would appear much more luminous than observed. The limits on the luminosity of the galaxies mean that black holes masses are of at most a few times $10^7\,\mathrm{M}_\odot$ contradicting quasar counts and integrated luminosities which imply black hole masses above 10^8 – $10^9\,\mathrm{M}_\odot$. Low-luminosity radio activity is very common in ellipticals (Sadler, Jenkins & Kotanij 1989; Wrobel 1991, Slee et al. 1994) indicating that indeed there is some kind of central engine in the cores of these galaxies.

The inconsistencies described above, can be reconciled by considering a situation in which the intrinsic radiative efficiency of the accretion is low. This has been noted by Fabian & Rees (1995) in the light of recent discussions of optically thin advection-dominated accretion solutions (Narayan & Yi 1995a,b; Abramowicz et al. 1995, Narayan, Mahadevan & Yi 1995 and references therein). In this mode of accretion, the accretion rate, $\dot{M}$, is low, the ions remain at the virial temperature and the radiative efficiency of the low density accreting material can be very small. The energy released by viscous friction is advected into the black hole.

Accretion of hot gas in an elliptical galaxy may create the ideal circumstances for a hot ion torus to form (Begelman 1986) and thus an advection-dominated accretion flow (ADAF) to operate *. In particular the successful application of low efficiency accretion via an ADAF in the giant elliptical galaxy M87 (which contains a $3 \times 10^9\,\mathrm{M}_\odot$ black hole – Ford et al. 1995; Harms et al. 1995) by Reynolds et al. (1997; Paper I) suggests that such mechanisms can be of wide importance. There, we found that the luminosity of M87 is consistent with the observations only if Bondi accretion from the hot gas involves an ADAF. X-ray observations provide us with core gas densities and therefore the means for estimating the Bondi accretion rate.

Here we present another example of a giant elliptical galaxy, M60 (NGC 4649), in which we believe accretion could be taking place via an ADAF. The giant elliptical galaxy M60 (NGC 4649) is an optically luminous galaxy in the Virgo cluster. It possesses very weak jets and small radio lobes indicating an active nucleus. The radio spectrum of the nucleus is weakly inverted (Fabbiano et al. 1987) as expected from an ADAF.

A deprojection analysis of data from the *ROSAT* High Resolution Imager (HRI) shows that the interstellar medium

* We note that the gas in the central region of elliptical galaxies is very likely to share angular momentum from stellar mass loss

(ISM) in M60 has a central density $n \approx 0.1\,\mathrm{cm}^{-3}$ for a sound speed $c_s = 300\,\mathrm{km\,s}^{-1}$ (C. B. Peres, private communication). The resulting Bondi accretion rate onto the central black hole is then

$$\dot{M}_{Bondi} = 3 \times 10^3 \left(\frac{M}{\mathrm{M}_\odot}\right)^2 \frac{n_\infty}{c_\infty^3} \quad \mathrm{M}_\odot \mathrm{yr}^{-1}. \tag{1}$$

If we assume a black hole mass of $\sim 10^9\,\mathrm{M}_\odot$ and a radiative efficiency of $\eta = 0.1$, the Bondi rate for a radiative efficiency of $\eta = 0.1$ predicts a luminosity of the order of $6 \times 10^{43}\,\mathrm{erg\,s}^{-1}$. We show here that the luminosity of the core of M60 does not exceed $10^{41}\,\mathrm{erg\,s}^{-1}$ and is probably less than $10^{40}\,\mathrm{erg\,s}^{-1}$ over all energies.

In this *Letter* we present a detailed examination of the possibility that the massive black hole in M60 accretes via an ADAF. In particular, we compute the spectrum expected and show that it is consistent with observations for a likely black hole mass ($\approx 10^9\,\mathrm{M}_\odot$) and reasonable mass accretion rates given by eqn.(1). In contrast to M87 (Paper I) the observations of M60 are not highly contaminated by jet emission and therefore provide tighter constraints on the model spectrum.

In Section 2 we compile data from the literature on the full-band spectrum of the core of M60 and present some additional data on the X-ray flux from the core. Section 3 describes some details of our ADAF model spectrum calculation. In section 4, we compare the model spectrum with the data and find that accretion rates comparable with the Bondi rate allow a black mass of $\sim 10^9\,\mathrm{M}_\odot$ at least.

2 THE SPECTRUM OF THE CORE EMISSION

2.1 The M60 data

In order to examine the nature of the accretion flow in M60, we have compiled the best observational limits on the full band spectrum of the core emission. Our aim is to obtain good observational limits on the core flux over a wide range of frequencies rather than to compile a comprehensive list of all previous observations. Some contribution from the weak jets and in particular from the underlying galaxy are unavoidable and so the derived spectrum should be considered an upper limit to that of the accretion flow at the core of M60. The data are summarized in Table 1.

Very Large Array (VLA) imaging by Stanger & Warwick (1986) and Wrobel & Heeshen (1991) shows an extended radio source dominated by a compact (< 4 arc–sec) core. The extended structure defines radio lobes powered by weak jets with linear dimensions $\sim 2\,\mathrm{kpc}$. The slowly-rising spectral nature of the high-frequency emission is well defined by the data of Fabbiano et al. (1987) obtained from the 100 m radio telescope of the MPIfR at Bonn.

Einstein observations of M60 reveal that the overall X-ray emission is extended with most of it arising from the hot gas at kT = 1 keV (Stanger and Warwick 1986).

We have examined the *ROSAT HRI* dataset in order to constrain the nuclear X-ray flux of M60. Here we present the *ROSAT* HRI data resulting from a 19 923 s exposure performed on 1995 June 21. Fig. 1 shows the *ROSAT* HRI image of M60. Consistently with the *Einstein* HRI observation, the *ROSAT* HRI image shows that M60 is extended

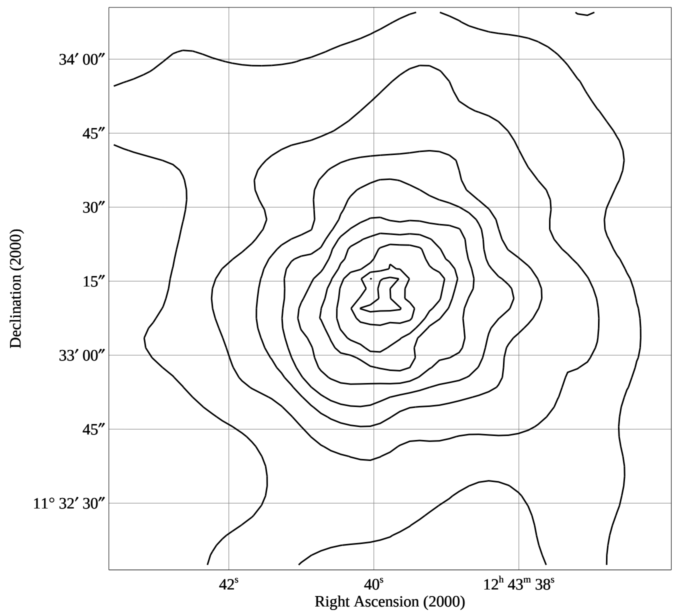

Figure 1. The core regions of M60 (NGC 4649) as imaged in a 20ks exposure with the *ROSAT* HRI. The distribution of the X-ray emission in the central region is quite complex and asymmetric. The diffuse emission is from the hot interstellar medium. The image has been smoothed adaptively prior to contouring; the minimum number of counts over which smoothing occurred is 25. Contour levels are equally spaced on a logarithmic scale, starting at 8×10^{-2}count s^{-1}arcmin^{-2} and increasing by a factor 1.6 between adjacent contours.

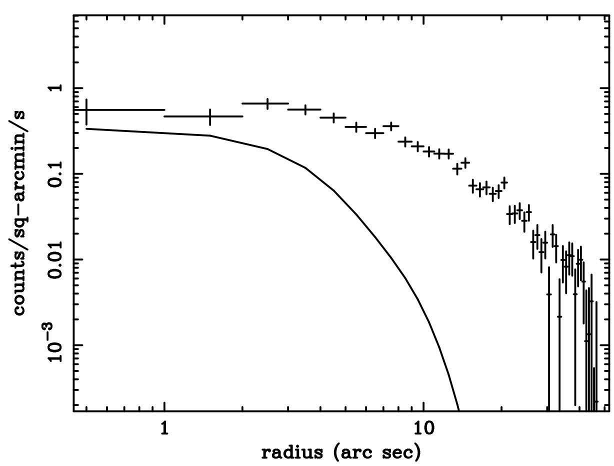

Figure 2. The contribution of a point source to the emission of M60. The solid line shows the PSF of the *ROSAT* HRI compared to the actual count rate per unit area.

X-ray source with most of the emission coming from hot gas in the interstellar medium. The low luminosity radio activity though, indicates that there is some form of active central engine in the core of M60. In order to find an upper limit to the nuclear emission of M60, we have considered an extended component modelled by a King pro-

Table 1. Summary of data for the core of M60.

Frequency ν (Hz)	νF_ν ($10^{-15}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$)	reference	notes
1.4×10^9	0.37	Hummel et al. (1983)	Westerbork
4.75×10^9	1.14	Fabbiano et al. (1987), Wrobel (1991)	Effelsberg, VLA
1.07×10^{10}	2.78	Fabbiano et al. (1987)	Effelsberg
3.3×10^{10}	10.5	Fabbiano et al. (1987)	Effelsberg
5.45×10^{14}	≤ 180	Byun et al. (1996)	HST
2.4×10^{17}	$\leq$150	this work	*ROSAT* HRI

file plus a point source modelled by the PSF of the HRI (see Fig.2). Our upper limit (at 90 per cent confidence) predicts a count rate from the point source component of $4.7 \times 10^{-3}\,\mathrm{ct\,s^{-1}}$ (Fig. 2). Assuming the spectrum to be a power-law with a canonical photon index $\Gamma = 2.0$ modified by the effects of Galactic absorption (with column density $N_{\rm H} = 3.0 \times 10^{20}\,\mathrm{cm^{-2}}$); this count rate implies a flux density at 1 keV of $F(1\,\mathrm{keV}) = 1.5 \times 10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}\ keV^{-1}}$. This result is fairly insensitive to the choice of power-law index.

3 ADVECTION-DOMINATED TORI

It has been found (Rees 1982; Narayan & Yi 1995ab; Abramovicz et al. 1995) that the advection dominated solution can occur only at accretion rates below $\dot{M}_{\rm crit} \approx \alpha^2 \dot{M}_{\rm Edd}$, where α is the Shakura-Sunyaev viscosity prescription and $\dot{M}_{\rm Edd}$ corresponds to the standard Eddington accretion rate. At such low accretion rate the cooling timescale for the ions exceeds the inflow timescale and most of the thermal energy is carried into the event horizon. The plasma is much hotter than in the classical, radiatively–efficient, thin disk solution and the flow consists of a thick torus. We assume that electrons and protons are coupled only by two–body Coulomb interactions and that electrons radiate by synchro-cyclotron, bremsstrahlung and inverse Compton processes. Since the Coulomb coupling is very weak, the ions remain at the virial temperature and very little energy is transferred to the electrons. The disk, in this solution, has low radiative efficiency.

For convenience, we rescale the radial co-ordinate and define r by

$$r = \frac{R}{R_{\rm S}}, \qquad (2)$$

where R is the radial coordinate and $R_{\rm S}$ is the Schwarzschild radius of the hole and the accretion rate,

$$\dot{m} = \frac{\dot{M}}{\dot{M}_{\rm Edd}}. \qquad (3)$$

The ADAF model, which is based on that of Narayan & Yi (1995) is the same as that used in Paper I for M87 (Reynolds et al. 1997). By assuming that the system is undergoing advection-dominated accretion, we can predict the radio–to–X-ray spectrum of the accretion flow. The amount of emission from the different processes and the shape of the spectrum can be determined as a function of the model variables: the viscosity parameter, α, the ratio of magnetic to total pressure, β, the mass of the central black hole, M, and the accretion rate, $\dot{m}$. For the moment, we take $\alpha = 0.3$ and $\beta = 0.5$ (i.e. magnetic pressure in equipartition with gas pressure). The electron temperature at a given point in the ADAF, $T_{\rm e}$, can then be determined self-consistently for a given $\dot{m}$ and M by balancing the heating of the electrons by the ions against the various radiative cooling mechanisms (within $r < 1000$, it is found that $T_{\rm e}$ is approximately constant in the range of parameter space of interest and it is $\approx 2 - 3 \times 10^9$ K). To determine the observed spectrum, we integrate the emission over the volume and take account of self-absorption effects. We have taken the inner radius of the disk to correspond with the innermost stable orbit around a Schwarzschild black hole, $r_{in} = 3$, and the outer radius to be $r_{out} = 10^3$ (for which the characteristic 2-temperature ADAF solution is mantained).

In Fig. 3 we show the spectrum of the advection-dominated disk for $m = 6.3 \times 10^8, 10^9, 1.6 \times 10^9$ where m is defined as $m = M/\mathrm{M}_\odot$ and *dotm* given by the Bondi accretion rate in eqn. (1). The peak in the radio band is due to synchro-cyclotron emission by the electrons in the magnetic field of the plasma. The X-ray peak is due to thermal bremsstrahlung. The power-law emission extending through the optical band is due to Comptonization of the synchro-cyclotron emission: more detailed calculations show this emission to be composed of individual peaks corresponding to different orders of Compton scattering. The positions at which the synchrotron and bremsstrahlung peaks occur and their relative heights depend on the parameters of the model. The synchrotron radiation is self-absorbed and locally gives a Rayleigh Jeans spectrum, up to a critical frequency, ν_c. The bremsstrahlung peak occurs at the thermal frequency $\nu \sim k_{\rm B} T_e/h$.

4 THE DATA VERSUS THE ADAF MODEL

Fig. 3 shows the data on M60 with predicted spectra for different black hole masses and the relative Bondi accretion rates. A strong feature of an advection–dominated solution is that the whole spectrum can be determined by few parameters. With α and β given the only two parameters left are m and $\dot{m}$. In Paper I we had an independent determination for the black hole mass, m, of M87. The only parameter to be determined was therefore the accretion rate. A comparison with the observational limits confirmed that the physically consistent accretion rate for such a system was indeed the Bondi rate. Here we therefore use the Bondi formula and vary the mass m. We find that the radio bounds on Fig. 3

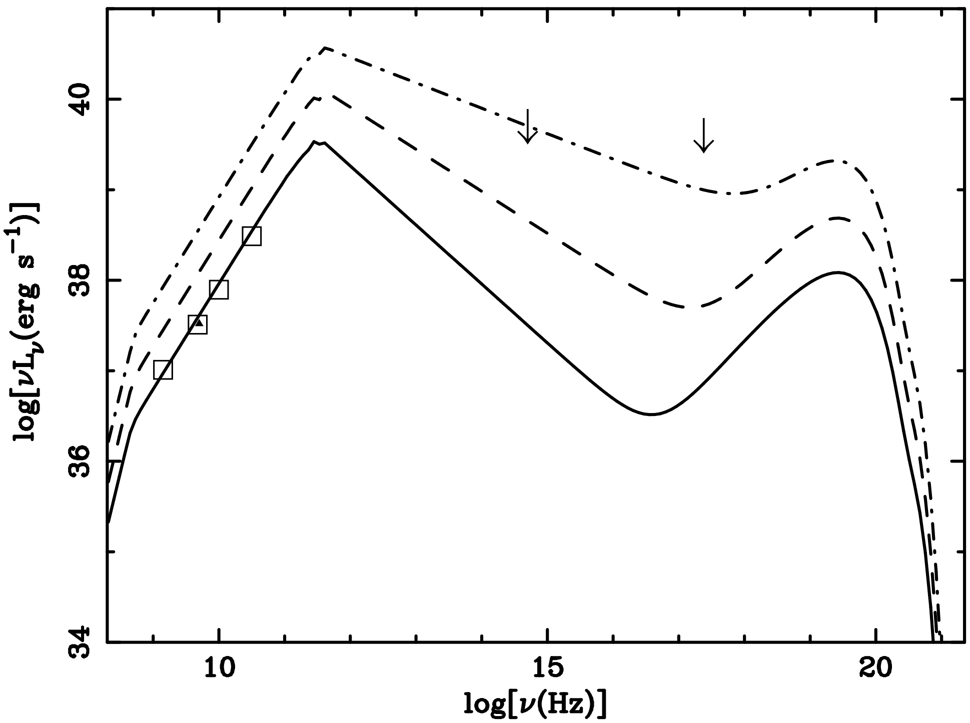

Figure 3. Spectrum of M60 calculated with an advection-dominated flow extending from $r_{min} = 3$ to $r_{max} = 1000$. The parameters are $\alpha = 0.3$, $\beta = 0.5$. Three model spectra are shown: for (i) $m = 10^{8.8}$−solid line, (ii) $m = 10^{9.0}$−dashed line, (iii) $m = 10^{9.2}$−dot-dashed line and their corresponding $\dot{m}$ given by Bondi accretion formula, eqn.(1). The squares represent the radio measurements and the arrows the upper bounds for the optical and X-ray core emission of M60 taken from the different references explained in the text. For M60, a distance of 15.8 Mpc is assumed.

allow black hole masses $m \approx 10^9$, similar to that required by independent arguments for dead quasars. For such masses, the low luminosity of the core of M60 is consistent with the data at different wavelengths only if the accretion involves an ADAF. Interestingly, the radio data points reproduce the slope ($\propto \nu^{2/5}$) of the self-absorbed synchrotron radiation (Mahadevan 1996) very well. Such agreement is even more evident than in M87 (Paper I) where contributions from the powerful jet had to be taken into account. It is important to point out that radio observations (Slee et al. 1994) of many bright elliptical galaxies typically show rising spectra with an average radio spectral index of 1/3.

5 SUMMARY

We have shown that if M60 consists of an advection-dominated system accreting from the hot interstellar medium at a rate determined by the Bondi formula, then the upper limit on nuclear black hole mass is much higher, $M \approx 10^9\,\mathrm{M}_\odot$, than that determined by Fabian & Canizares (1988), $M \leq$ few$\times 10^7\,\mathrm{M}_\odot$.

The poor efficiency of this advective accretion mode accounts for the low luminosity observed and allows for black hole masses of the order of $10^9\,\mathrm{M}_\odot$ consistent with the idea that bright ellipticals like M60, host dead quasars.

This conclusion is strengthened by the previous application of a similar model to the well known active nucleus in M87, which has a nuclear black hole mass of $3 \times 10^9\,\mathrm{M}_\odot$ and luminosity several orders of magnitude fainter than that expected from the Bondi solution (Paper I).

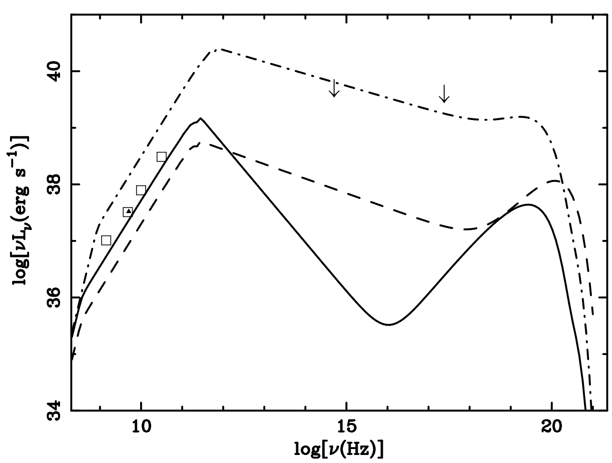

Figure 4. Spectra of M60 calculated for $m = 10^{8.8}$. The effects of varying α and β are shown. (i) the dashed line is obtained for $\alpha = 0.3$ and $\beta = 0.95$, (ii) the solid line for $\alpha = 0.5$ and $\beta = 0.5$ and (iii) the dot-dashed line for $\alpha = 0.1$ and $\beta = 0.5$

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An important test for this model would be high fre-

quency radio/submm observations. These should reveal an abrupt spectral turnover above the inner self-absorbed frequency ($\sim 3\times10^{11}$ Hz) predicted by the model. Observations of the turnover would constrain the allowable viscosity and magnetic parameters α and β. Fig. 4 illustrates how different combinations of α and β are either ruled out by the available data or constrained by the higher frequency observations. In particular, we suggest that α and β should be anticorrelated for a given mass in order to have agreement with observations. This means that for relatively low values of α (~ 0.1 within the context of ADAF) require magnetic fields below their equipartition value (i.e. $\beta > 0.5$), for a black hole mass $\sim 10^9\,\mathrm{M}_\odot$.

High radio frequency polarization and interferometry studies could indicate and resolve the torus perpendicular to the jet. Better constraints on the X-ray flux will only be obtained with the improved resolution of AXAF.

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